Inverse Radiative Transfer Analysis for Ocean Optics

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LONG-TERM GOALS

The long-term goal of this research is to support the work of ocean optics experimentalists by developing analytical and numerical methods for solving radiative transfer inverse and forward problems. The ongoing research on inverse problems includes methods for obtaining the absorption and scattering coefficients, the spatial profile of sources (inelastic scattering, bioluminescence, and/or fluorescence), and the bottom albedo from radiance or irradiance data at a specified measurement wavelength. The development of new techniques for solving forward radiative transfer problems can be used to improve algorithms for solving inverse problems.

SCIENTIFIC OBJECTIVES

One short-term objective was to numerically test an algorithm for obtaining the absorption and backscattering coefficients from measurements of the downward and upward irradiances at depths where the directional nature of the surface illumination is relatively unimportant. A second objective was to numerically test an algorithm to infer the spatial dependence of sources at a specified wavelength from downward and upward irradiances. A third objective was to develop a single scalar radiative transfer equation that approximately accounts for the effects of polarization, which normally must be analyzed by solving four coupled equations for the Stokes parameters I, Q, U, and V.

APPROACH

The radiative transfer equation is the basis for both the analytical development and numerical testing of the inversion algorithms. In addition to myself, this research is being conducted by graduate students Robert Leathers and Lydia Sundman.

Inverse methods are being analytically derived that require little or no iteration and are especially useful for processing large amounts of data; they also can be used as initial estimates for iterative methods.

The numerical simulations of forward problems used to test the algorithms are performed for different surface illuminations, bottom boundary conditions, and source and/or inherent optical property spatial profiles.

WORK COMPLETED

Inverse Problem For Inherent Optical Property Estimation. A method was numerically tested in Refs. 1-3 for estimating the absorption coefficient a and the backscattering coefficient b_b from measurements of the upward and downward irradiances $E_u(z)$ and $E_d(z)$. With this method the reflectance ratio $R(z)$ and the downward diffuse attenuation coefficient $K_d(z)$ were obtained from $E_u(z)$ and $E_d(z)$, and the values of the inherent

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optical properties $R_{¥}$ and $K_{¥}$ were estimated from $R(z)$ and $K_d(z)$, respectively. For an assumed scattering phase function *b/b* there are unique correlations between the values of $R_{¥}$ and $K_{¥}$ and those of a and b_b that can be derived from the radiative transfer equation. To improve performance where bottom effects are important, two reflectance models for deep- and shallow-measurements were also developed.

Numerical testing has begun with the deep- and shallow-water reflectance models for the estimation of the albedo of the sea bottom.

Inverse Problem For Source Estimation. A method was numerically tested in Ref. 4 for determining the spatial distribution of a source (e.g., due to inelastic scattering, fluorescence, or bioluminescence) from upward and downward irradiance measurements $E_u(z)$ and $E_d(z)$ at a single wavelength in seawater of known absorption and scattering properties. The algorithm uses measurements at two depths located an arbitrary distance apart and solves for two parameters that fit a globally exponential or linear source shape. Estimates from neighboring measurement pairs can be pieced together to produce a global solution. In this way complex spatially-dependent source shapes can be estimated from an irradiance profile. Numerical tests illustrate the sensitivity of the algorithm to depth, measurement spacing, chlorophyll concentration, sensor noise, and uncertainty in the *a priori* assumed inherent optical properties.

Forward Problem For Polarization Analysis. An asymptotic analysis of the radiative transfer equation with polarization was developed in Ref. 5 that leads to a renormalized scalar equation for the total specific intensity of radiation I, the first Stokes parameter. The resulting scalar equation can be used without the complexity of performing vector radiative computations since it merely requires an adjustment of the Legendre coefficients of the scattering phase function using elements of the 4x4 scattering phase matrix. The equation is accurate to first order in the smallness parameter of the asymptotic analysis. Asymptotically consistent quadrature results also were obtained for the other three Stokes parameters Q, U, and V.

Forward Problem For Scalar Irradiance Peaking Analysis. When a highly-scattering, optically-thick medium is illuminated at its surface, it is possible under certain conditions for the scalar irradiance $E_0(z)$ to increase with penetration depth near the surface, even if there are no internal sources at the wavelength of interest. Analysis and numerical examples in Ref. 6 help explain and quantify the magnitude and location of potential $E_0(z)$ peaks in source-free ocean waters and the dependence of the phoenomenon on the seawater optical properties and surface illumination.

RESULTS

Inverse Problem For Inherent Optical Property Estimation. Good estimates of a and the Gordon parameter $G = b_b /(a+b_b)$ were obtained from $R_{¥}$ and $K_{¥}$ if the true scattering phase function was not greatly different from the assumed function. The method works best in deep homogeneous waters, but has been shown to be applicable in some cases to stratified waters. Because b_b is known to be quite sensitive to the backscattering portion of the phase function, it is important to use a realistic scattering phase model (e.g., a Petzold phase function) in the inverse solution.

Inverse Problem For Source Estimation. The algorithm works well with widely-spaced measurements, moderate sensor noise, and moderate uncertainties in the inherent optical properties, regardless of whether the assumed and true profiles are the same shape. Near the surface the presence of surface illumination results gives a significant over-estimation of the source magnitude; however, measurements of the surface illumination could be used to remove much of this effect. Using the algorithm in a piecewise fashion was found to be the best application of this algorithm. Large jump discontinuities between different layers suggest that either the data is very noisy or that the profile being estimated is not in complete agreement with the *a priori* assumed shape. Even in cases where the discontinuities were large, the overall estimation of the shape calculated in this piecewise fashion was very good. Results also showed that although a source that varies linearly with depth may seem to be a bad assumption, in practice a linear fit between the measurements can be very practical.

Forward Problem For Polarization Analysis. Numerical results demonstrated the improved accuracy of the renormalized scalar equation for the intensity over the usual unpolarized approximation. The percent error obtained for the asymptotic diffuse attenuation coefficient using the approximate scalar equation that incorporates effects of polarization is generally of the order of a factor of five--and in some cases a factor of ten--smaller than the error if polarization effects are totally ignored. The results vary considerably with the albedo of single scattering and the scattering phase function.

Forward Problem For Scalar Irradiance Peaking Analysis. Peaking of $E_0(z)$ is caused primarily by the portion of the illumination that is incident at small polar angles and scatters into directions within the downward hemisphere. Peaking is most pronounced when the incident illumination is strongly directed at the zenith angle, and the location of maximum is deepest when the asymmetry of the scattering phase function is large. The presence of internal reflection due to the index of refraction mismatch at the air-sea interface greatly reduces the chance of $E_0(z)$ peaks being present, making a maximum in $E_0(z)$ below the surface only possible if the single scattering albedo $\varpi > 0.95$ in homogeneous waters or potentially smaller values if ϖ increases with depth.

IMPACT/APPLICATION

Estimation of inherent optical properties is a primary goal of optical oceanographers for use in environmental monitoring. Inversion of the light field to determine inherent optical properties from apparent optical properties has direct application to in-water and remote sensing of ocean color. This inversion is more difficult for coastal waters than for open ocean waters because chlorophyll concentration cannot be used to correlate the properties. The analytically-based algorithms under development here will help in this inversion process and in obtaining optical closure.

TRANSITIONS

The efficacy of our approach for the estimation of a and b_b from either $E_u(z)$ and $E_d(z)$ or the vertically upward radiance $L_u(z)$ and $E_d(z)$ will be tested by Robert Leathers with experimental data collected from stations in Long Island Sound collected under the direction of Collin Roesler. Data from the same stations will be used to test our algorithm for estimating the bottom albedo.

RELATED PROJECTS

An iteration-based approach for estimating a and b_b has been developed with ONR support by Gordon and Boynton (Ref. 7) that differs from the analytical-based approach developed by us; in the future we anticipate merging the two techniques to gain the advantages of both. A new analytically-based algorithm for estimating a and b_b recently was developed under NRL support by Haltrin (Ref. 8) and in Ref. 3 we have numerically compared it to the algorithm developed by us. Our work on the importance of not neglecting polarization effects is related to work done by Adams and Kattawar in Ref. 9

with ONR support, while our research on estimating the bottom albedo is closely related to results reported by Ackleson in Ref. 10.

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